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SCIENCE DIRECT
Renewable and Sustainable Energy Reviews
10 (2006) 312–340
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands

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Received 17 September 2004; accepted 17 September 2004

Abstract

A significant number of islands have found themselves obliged to place restrictions on the penetration of renewable sourced energy in their conventional electrical grid systems. In general, this has been due to certain energy related characteristics often connected to their very nature as islands. These limitations attempt to prevent the appearance of problems that might affect the stability and safety of the electrical system. The restrictions imposed on the direct penetration of wind sourced energy in the conventional grids of the Canary Islands are an obstacle to meeting the renewable energy objectives set out by the European Union. As a partial solution to the problem, this paper proposes the installation on Gran Canaria island (Canarian Archipelago) of an appropriately administered wind powered pumped hydro storage system. The results obtained from the application of an optimum-sized economic model of such a system indicates that penetration of renewable sourced energy can be increased by 1.93% (52.55 GW h/year) at a competitive cost for the unit energy supplied. These results are obtained on the hypothesis that two of the largest existing reservoirs on the island (with a difference in height between the two of 281 m and a capacity of some 5,000,000 m^3 used in each) are employed as storage deposits. Investment, operating and maintenance costs are taken into account, as well as those costs involving health and environmental damage associated with energy production and use (externalities). The system would consist of: a wind farm with a rated output of 20.40 MW; a modular pumping station with a rated output of 17.80 MW, operated so that the variation in the energy demand for pumping is in sympathy with

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.09.005

the wind generation; and a hydraulic plant with a rated output of 60.00 MW. The proposed system would have no negative effect on either the reliability of the electrical system or consumer satisfaction. Furthermore, it would mean a fossil fuel saving of 13,655 metric tonnes/year and a reduction in CO_2 emissions into the atmosphere of 43,064 metric tonnes/year. For regions that have topographically suitable sites and which suffer energy problems similar to those of the Canary Islands it is thus suggested that an analysis be made of the technical and economic feasibility of the installation of power systems such as that proposed in this paper. Within the general guiding framework of a policy promoting clean and renewable energy, these systems represent an enormous and as yet barely explored potential.

Keywords: Wind energy; Wind energy penetration; Pumped hydro storage; Hydropower

Contents

1. Introduction

The Canarian Archipelago, made up of seven islands (Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Palma, La Gomera and El Hierro),[1] is one of the 17 autonomous communities belonging to the Spanish State and one of the outermost regions of the European Union. The islands are located north-west of the African Continent, between

[1] And six islets, most of which are uninhabited.

Nomenclature

δ	the percentage δ of peak demand which is to be covered with hydraulic energy, %
η_{PS}	efficiency of the PS
η_{HP}	efficiency of the HP and its electrical system
ϕ	wake factor
ρ	water density, kg m^{-3}
ξ	reliability factor of the WT
C_{EXT}	external costs, euros
CI_0	investment costs of the electrical and control infrastructure, euros
$C_{O\&M}$	annual operating and maintenance costs, euros
CP	conventional electrical generator set
CPS	conventional electrical power system
CS	control system
$D_{LS}(t)$	electrical demand in time t, kW
$[D_{LS}(t)]_{base}$	base demand in time t, kW
$[D_{LS}(t)]_{peak}$	peak demand in time t, kW
$D_{LS,max}$	maximum peak demand, kW
$D_{PS}(t)$	pump load system power demand, also called controllable loads, in time t, kW
$D_{total}(t)$	total demand requested by the different loads, controllable and non-controllable, in time t, kW
g	acceleration due to gravity, m s^{-2}
h_e	height of the rotor shaft of the WT, m
H_b	pumping height, m
H_n	net height, m
HP	hydroelectric plant
h_r	height of wind speed measurement, m
HT	hydraulic turbine and its corresponding electrical generator
H_u	useful height, m
L	number of years over which the investment in the system is to be recovered, years
LR	lower reservoir
LS	load system
MP	motor pumps
nt	number of hydraulic turbines and their corresponding electrical generators which make up the hydroelectric plant
$n_{tc}(t)$	number of HT connected at the instant t
n_p	number of motor pumps of the subsystem PS
nw	number of wind turbines which make up the wind farm
$n_{pc}(t)$	number of pumps connected at the instant t
$P_{CPS}(t)$	conventional power of the CPS in time t, kW

$P_{HP}(t)$	hydraulic power of the HP in time t, kW
$P_{total}(t)$	total power generated by a combination of components which must satisfy the demand $D_{LS}(t)$, kW
$P_{WF}(t)$	wind power of the WF in time t, kW
$P_{WT}(v)$	characteristic curve of the WT
PS	water pumping station
$Q_p(t)$	volume pumped by a MP at each instant, $m^3\,h^{-1}$
$Q_t(t)$	volume used by a HT at each instant, $m^3\,h^{-1}$
r	annual discount rate (opportunity cost)
S_0	initial subsidy, euros
Δt	simulation interval (1 h)
UR	upper reservoir
$V(t)$	volume of water in the upper reservoir at time t, m^3
$v_e(t)$	wind speed, extrapolated at height h_e of the rotor shaft of the WT, as a function of time, $m\,s^{-1}$
V_{min}	technical minimum volume of water required in the upper reservoir so that the turbines can operate, m^3
$V_p(t)$	volume of water pumped by the PS in time t, m^3
$v_r(t)$	wind speed, recorded at a reference height h_r, as a function of time, $m\,s^{-1}$
$V_t(t)$	volume of water used by the HT, m^3
WF	wind farm
WS	water storage system
WT	wind turbine
z_0	surface rugosity, m

latitudes 27°37′ and 29°25′ north (subtropical) and longitudes 13°20′ and 18°10′ west of Greenwich (see Fig. 1).

The geographical fragmentation of the Canary Island Autonomous Community, its separation from the major centres of energy production and consumption,[2] and the lack of conventional energy resources have meant that its inhabitants have had to depend to a large extent on the import of petroleum to supply its energy needs. However, the Canary Islands have abundant renewable energy sources at hand, principally the wind and the sun. The wind resources in particular are especially high, both in terms of intensity and constancy [1,2].

As a result of the energy plans that have been developed [2], employing renewable sourced energy to alleviate the practically total dependency on fossil fuel energy, the rise in the use of wind sourced energy in the Canaries has been spectacular. In the year 2002 a total of 41 wind farms were in operation with an installed power of 105.60 MW and a

[2] The shortest distance between the Archipelago and mainland Spain is some 1000 km.

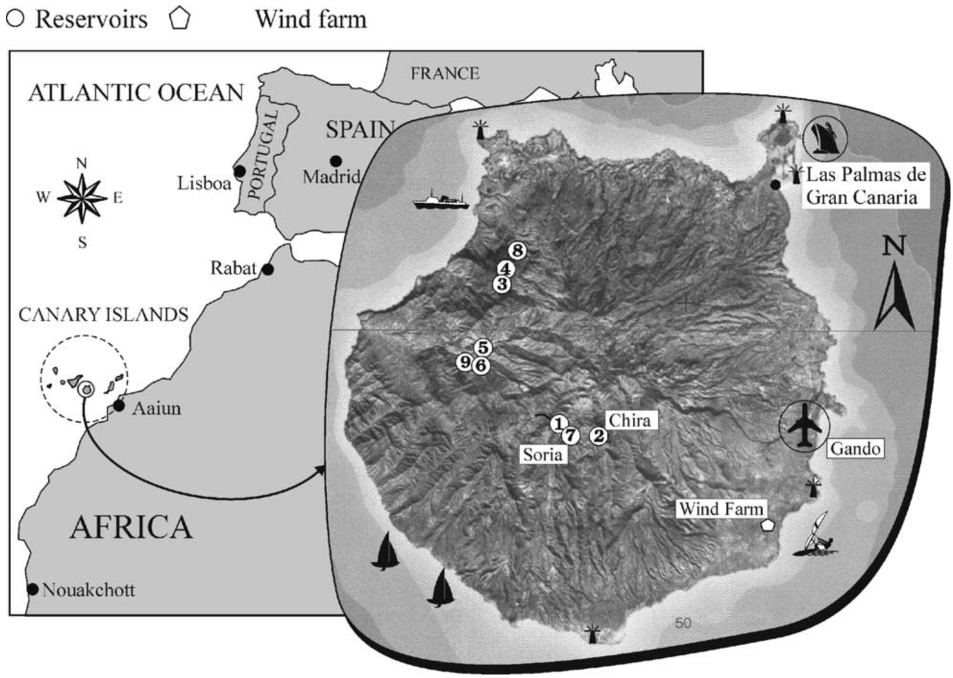

Fig. 1. Geographical location of the Canarian Archipelago.

total production of 243 GW h (2002). This, in turn, meant for 2002 a reduction in CO_2 emissions of 200,208 tonnes and a primary energy saving of 61,785 tonnes.

It should be mentioned that the Canary Island Autonomous Community was one of the pioneer Communities in Spain regarding wind energy exploitation and the installation of wind farms. In fact, and despite its relatively small size,[3] 34.66% of the total wind power installed in Spain in 1994[4] was from the Archipelago. In this year Spain was the fifth highest wind sourced electrical energy producer within the European Union [2]. The spectacular increase in installed wind power in Spain during the nineties took the country to second position, behind Germany, at the end of 2000; a position it still held at the end of 2003. However, despite its still having at the end of 2000 a high percentage of installed wind power compared to most European Union countries [2], for technical reasons the Canary Island Autonomous Community has been unable to follow the growing trend of the installation of wind farms in the rest of the Spanish State; and this in spite of the fact that the Archipelago has an as yet unexploited high wind potential.

The technical reasons alluded to above are related to the structure of the islands' electricity generating systems (each island has an independent small-medium sized power system). A number of serious problems can appear when trying to maximise the

[3] The total surface area of the Archipelago is 7,446.62 km^2 (approximately 1.5% of all Spanish territory).

[4] Until 1996 the Canarian Archipelago held second position among the 17 Autonomous Communities of Spain in terms of wind power installed and wind energy produced.

percentage of electrical energy demand that can be covered by the direct feeding of wind sourced energy in a small or medium sized electrical system. At high levels of wind sourced energy penetration, the variations in the active power generated (due to variations in the wind speed) cause disturbances between the power generation and power demand of the system, giving rise to frequency and voltage variations which could lead to dangerous operating conditions [3,4]. To avoid serious problems (that could affect the safety and stability of the electrical system) wind sourced energy generation has to be limited to a specific percentage of the conventional synchronous capacity connected to the grid, which in turn depends on the load of the system [3,5]. The Ministry of Industry and Energy of the Canary Government, as a result of these technical arguments, has imposed restrictions on the exploitation of the available wind potential through wind farms connected to the conventional grid. It should be mentioned in reference to these restrictions that this body has also laid down a series of regulations governing the Registration of Production Installations under Special Regime and favouring those installations whose objective is to use wind sourced energy for self-consumption.

Notwithstanding the above, and with the aim of meeting the principles and targets outlined by the European Union in energy related matters [6,7], the Canary Government has not ceased in its search for solutions that would allow the high wind potential available in the Archipelago to be fully exploited to its maximum. These solutions aim to: (a) guarantee the energy supply; (b) reduce the degree of vulnerability of the supplies by diversifying the sources; (c) promote the rational use of energy; (d) reduce energy dependence on external sources by increasing as much as possible the use of new energy sources; (e) guarantee a stable and safe energy supply; (f) minimise energy costs; (g) contribute to the protection and conservation of the environment.

In this context, two lines of activity can be distinguished within a policy of promoting clean and sustainable energy. Firstly, research into and the installation of renewable sourced energy production systems isolated from the island grids. These range from hybrid wind-diesel systems aimed at fully supplying the energy needs of isolated villages [8,9], to electrical energy production systems which exclusively use wind sourced energy for sea water desalination [10,11] as a means of storing the kinetic energy of the wind in the form of desalinated water which can then be used for human or agricultural consumption. Secondly, and in relation to the use of hydropower systems, the possibility is being analysed of installing wind powered pumped hydro storage systems as a means of increasing in a reliable and dependable way [12,13] the penetration of wind energy (converted into hydraulic energy) into the electrical grid.

This paper presents the results obtained from the application, in the island of Gran Canaria, of a model for the optimum economic sizing of the various components that make up a wind powered modular hydro pumped system. The aim with this system is to cover a percentage of peak demands using already existing reservoirs as storage deposits. Special mention is made of the feasibility study carried out to increase wind energy penetration in the island's electrical grid system with the installation of a hydropower system with 'positive feed-forward' [14].

There are numerous islands all over the world with energy problems similar to those experienced in the Canarian Archipelago [15]. For regions with wind resources and topographically suitable sites it is thus proposed that an analysis be made of the

technical and economic feasibility of the installation of power systems such as that described in this paper. Within the general guiding framework of a policy promoting clean and renewable energy, these systems represent an enormous and as yet barely explored potential.

2. Characteristic features of the island of Gran Canaria

To facilitate an understanding of the proposals of this paper a brief description is provided here of the basic features of Gran Canaria, its present energy situation and its hydrographic characteristics.

2.1. General features

The island of Gran Canaria, located in the centre of the Archipelago, is almost circular in shape (Fig. 1), with a width of 47 km and a length of 55 km. It is a large rocky massif which peaks near to its geographical centre at an approximate height of 2000 m. The surface area of the island is some 1532 km^2 and with 755,489 inhabitants it is the most populated of the Canary Islands.

Though industrial activity in general is low throughout the Archipelago, Gran Canaria is the island with the highest industrial diversification,[5] as well as the highest geographical concentration of that industry (some 60% of the industrial activity is absorbed by its capital, Las Palmas de Gran Canaria). However, tourism is the most developed sector,[6] with a decisive influence in many service areas.[7]

2.2. Energy situation

Unión Eléctrica de Canarias, S.A. (UNELCO) is the company which produces and sells energy on the island. The private service in this field has practically disappeared together with the small businesses that were operating just two decades ago.

The total thermal electrical power installed in Gran Canaria at 31 December 2002 amounted to 715.36 MW, spread among three power stations as shown in Table 1. Total electricity production from the power stations during 2002 amounted to 2,725,570.55 MW h, with a fossil fuel consumption of 681,175 metric tonnes.

In terms of renewable sourced energy, Gran Canaria is the island with the highest installed power in the Archipelago. Wind sourced power connected to the island grid at the end of 2002 amounted to 74,535 kW, entailing 10.42% of conventional power, with total electricity production in 2002 of 128,588,336 kW h; this means an overall annual

[5] The industrial sector share in terms of GAV (gross added value) was in the order of 8.93% in 1993.

[6] The Canary Islands is one of the leading tourist centres in the world. The months from December to March are the busiest with tourists seeking refuge in the warmer temperatures of the winter on the islands. Gran Canaria and Tenerife are the two islands with the highest number of visitors. Of the 10,137,202 foreign tourists who visited the Archipelago 2,352,880 stayed in Gran Canaria.

[7] The tourist activity generates, directly or indirectly, some 17.36% of employment on the island.

Table 1
Conventional electrical power installed in Gran Canaria at the end of 2002

Plant's name	Technology	Number of sets	Unitary power (MW)	Total power (MW)
Guanarteme	Gas turbine	2	17.20	34.40
	Steam turbine	2	60.00	120.00
	Steam turbine	2	40.00	80.00
	Steam turbine	1	33.15	33.15
Jinámar	Diesel plant	2	24.00	48.00
	Diesel plant	3	12.00	36.00
	Gas turbine	2	37.50	75.00
	Gas turbine	1	23.45	23.45
Tirajana	Steam turbine	2	80.00	160.00
	Gas turbine	2	37.50	75.00
Emalsa	Steam turbine	2	12.10	24.20
Negrin	Diesel plant	2	3.08	6.16
Total		23		715.36

penetration of 4.72% of renewable sourced energy fed into the grid. The wind farms are generally located in the south-east of the island, due principally to the intensity and constancy of the winds in this area, the availability of easily accessible land, the presence of high voltage grids, etc. The wind farm with the highest installed capacity (20.10 MW) is made up of 67 wind turbines of 300 kW, while the highest installed rated output of a wind turbine on the island is 650 kW.

However, as previously mentioned, any increase in the number of wind farm installations connected to the general electricity grid has been restricted by the Ministry of Industry and Energy of the Canary Government, though regulations have been laid down favouring those installations whose objective is to use wind sourced energy for self-consumption [2]. In other words, preferential treatment is given to those wind installations whose instantaneous power balances do not mean the feeding into the grid, even occasionally, of a significant percentage of the energy that they generate. As a general principle, the reference maximum wind power that could be installed in the year 2011 in the island's electrical system is 362 MW. The Autonomous Ministry responsible for energy related matters determines, through the pertinent studies that are undertaken and in function of the evolution of demand and the technical restrictions of the thermal generator sets, the amount of wind sourced power that can be connected by degrees to the electrical grids.

At 30th December 2003, the total installed surface area of solar energy panels was estimated at 20,515.87 m^2. In terms of installed photovoltaic power, isolated from the electrical grid, the total estimated amount at the same date was 55,456 kW.

2.3. Hydrological situation

The climate in the Canary Islands is mild and undergoes only very slight seasonal variations over the year. However, there are regional climatic differences which give rise to a wide variety of landscapes. The hydraulic reality of the islands is closely linked to the absence of rains. In this sense, the Canary Islands find themselves somewhere between

Fig. 2. Views of the reservoirs of Soria and Chira.

the rainfall typical of a desert region and that of a temperate climate, though there are highly marked differences between islands and between regional areas on each island depending on factors such as altitude and orientation.

Average rainfall in Gran Canaria is 466 h m^3 (300 mm), the estimated volume of evapotranspiration is 304 h m^3/year (195 mm), and water runoff is 75 h m^3/year (48 mm). Water infiltration amounts approximately to 87 h m^3/year (57 mm).

In Gran Canaria exploitation is made of both underground and surface water. Surface water is basically exploited through the use of reservoirs (Fig. 2).[8] There are a total of 60 reservoirs located mainly in the south-west region of the island (where the land is less permeable and where there is a higher number of ravines/gullies), with a total storage capacity[9] of 76.8 h m^3.

Disregarding those reservoirs with a storage capacity of less than 1 h m^3, the transfer of water from some reservoirs to others (Table 3 and Fig. 1) is feasible,[10] recovering thereby the potential energy of that water by using the existing difference in heights of the reservoirs.

[8] The reservoirs are deposits generally formed by closing the channel of a ravine or gully with a dam.

[9] 12% of the dammed capacity constitutes the average year-on-year volume of water used in the island.

[10] In fact, there are existing pipelines which connect some of these reservoirs to transfer water, though not for energy exploitation purposes.

3. Pumped hydro storage systems

In conventional electrical energy production systems the generating plants have to cover fluctuations in demand, with peak periods possibly representing a high percentage of actual consumption, while still trying to maintain minimum costs [16]. These demand peaks are generally supplied by what are known as 'cyclical plants', which are smaller in size and output than the conventional plants used to cover the base demand. The cyclical plants tend to be powered by coal, fossil oil or gas but also operate using cyclical pumped storage systems. The pumped hydro storage systems use excess electricity production, in periods of low demand, to pump water to a deposit situated at a certain height, recovering it at a later time through a turbine when it is required to cover peak load periods [17,18]. The technological advances made since the first pumped hydro storage systems were built between 1910 and 1927 have meant a spectacular increase in total installed world capacity [19]. Nowadays pumped hydro storage systems are considered by engineers and planners to be an attractive alternative for the expansion of power systems [19,20], as a considerable amount of energy can be stored with this technique, the generating equipment is highly reliable [17,20,21] and the power output can be extensively regulated maintaining a practically constant efficiency within the generated power range [18].

Another reason that has awoken interest in the large scale use of hydro storage systems since the 1970s has been the increase in the use of renewable energy sources to generate electricity. In this sense, various projects have been proposed, particularly in the USA, aimed at adding the use of wind energy to already existing hydroelectric power stations [22–30], as well as projects for small sized hybrid systems, fundamentally in Europe and Asia [31–37].

When one of the power subsystems involved in electricity generation produces energy with a high random component, as is the case of a wind farm where the energy output depends on the wind speed, there exists uncertainty as to the availability of sufficient energy at any one instant to cover demand. One form of reducing this uncertainty, and thus ensuring customer satisfaction by not placing limits on demand, is through the installation of an energy storage system that enables adaptation of the irregular nature of the supply from wind turbines to the irregular nature of the demand. Though there are proposals to increase the use of renewable sourced energy in island electricity grids through the storage of hydrogen [15],[11] the only feasible means of storing large quantities of electrical energy at the present time is using pumped storage systems [17,18]. However, as various authors have pointed out [14,17,21], hydro storage systems may present a number of problems such as, for example, the environmental damage caused by reservoirs and the difficulty of finding topographically suitable sights with sufficient water capacity to make the installation of such systems profitable.

[11] In this reference a model optimisation and energy planning of integration of hydrogen storage for Porto Santo island (Madeira archipelago—Portugal) is presented. However, though the authors conclude that it is possible to significantly increase the penetration of renewable energy sources with a relatively high cost, what that cost is not mentioned. According to Ramage [17], the storage of large quantities of energy in hydrogen form can perhaps be used at some future time.

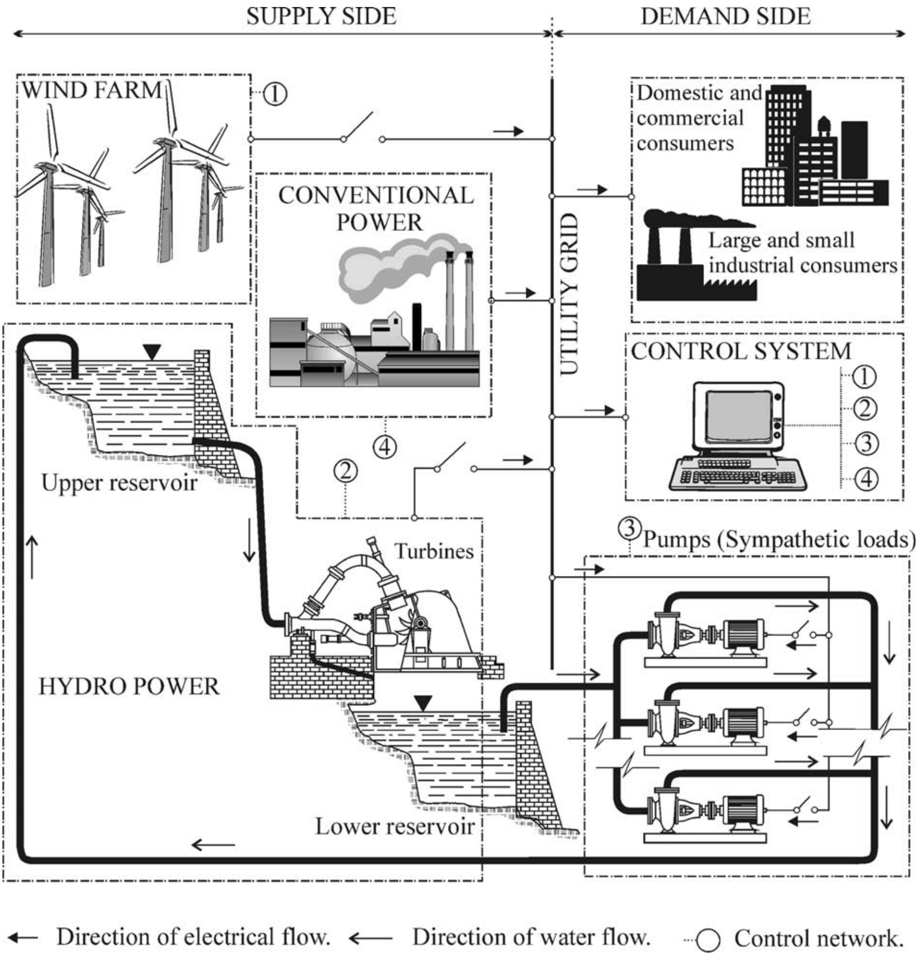

Fig. 3. Schematic representation of the proposed system.

3.1. General outline of the proposed system

Fig. 3 shows an outline of the most general configuration of the proposed system [38]. It consists of a wind farm (WF) with nw identical wind energy conversion systems (WT); a hydroelectric plant (HP) of nt identical hydraulic turbines and their corresponding electrical generators (HT); a water pumping station (PS) with n_p identical motor pump sets (MP); a water storage system (WS), consisting of a lower (LR) and upper (UR) reservoir; a control system (CS);[12] a conventional electrical power system (CPS); and the load system (LS).

[12] From the technical point of view it would preferable for the proposed CS to control all the subsystems. However, this system could only control the subsystems 1, 2 and 3 after negotiation with the company that controls the conventional subsystem 4.

The LS is dependant on the load structure (domestic, industrial, commercial) and the climatic characteristics of the region whose energy requirements the system aims to cover, but which here are considered uncontrollable by the CS.

As can be seen in Fig. 3, the various power and load subsystems in the proposed model are connected to the same electrical grid.[13] The advantage of this system configuration is that the WF can be located in an area of high wind potential which does not have to coincide with the installation area for the PS. However, its peculiarity lies in the fact that if the aim is to maintain the stability of the system without compromising its reliability, then it requires the CS to be able to control part of the demand in addition to the energy supply. The means proposed for such a control are discussed below in 'model formulation'.

3.2. Model formulation

For the proposed system to operate correctly there must exist a balance between the total electrical power $P_{\mathrm{total}}(t)$ fed into the grid by the three types of power subsystems involved, Eq. (1), and the total demand $D_{\mathrm{total}}(t)$ required by the various loads, Eq. (2). In other words, at each instant t Eq. (3) must be met.

$$P_{\mathrm{total}}(t) = P_{\mathrm{WF}}(t) + P_{\mathrm{HP}}(t) + P_{\mathrm{CPS}}(t) \tag{1}$$

$$D_{\mathrm{total}}(t) = D_{\mathrm{PS}}(t) + D_{\mathrm{LS}}(t) = D_{\mathrm{PS}}(t) + [D_{\mathrm{LS}}(t)]_{\mathrm{base}} + [D_{\mathrm{LS}}(t)]_{\mathrm{peak}} \tag{2}$$

$$D_{\mathrm{total}}(t) = P_{\mathrm{total}}(t);\ \ \forall\, t \tag{3}$$

where

$P_{\mathrm{WF}}(t)$ electrical power supplied by the wind farm in time t
$P_{\mathrm{HP}}(t)$ electrical power supplied by the hydraulic turbines in time t
$P_{\mathrm{CPS}}(t)$ electrical power supplied by the conventional system in time t
$D_{\mathrm{LS}}(t)$ power demand of the system of loads uncontrollable by the CS (domestic and commercial consumers, large and small industrial consumers, etc.) in time t
$D_{\mathrm{PS}}(t)$ power demand of the pump load system, also referred to as controllable or 'sympathetic loads', in time t

Generally, in conventional power systems, the control subsystem acts exclusively on power output, attempting to adapt the energy supply to demand with the aim of maintaining an energy balance (negative-feed-back control [14]). If output is higher than demand the control subsystem reduces output and if load is higher than output then output is increased through the use of additional power.

In order to maintain the stability of the proposed electrical system (Fig. 4), without compromising the system reliability or customer satisfaction, it is proposed that the CS can

[13] In the event that the grid has connection problems with the proposed system, an alternative system could be configured [38]. Then, the WF and the PS would be connected to an independent electrical grid, with the WF–PS–operating in a similar manner to that analysed by Carta et al. [10], for the case of a stand-alone wind farm connected to a modular desalination plant.

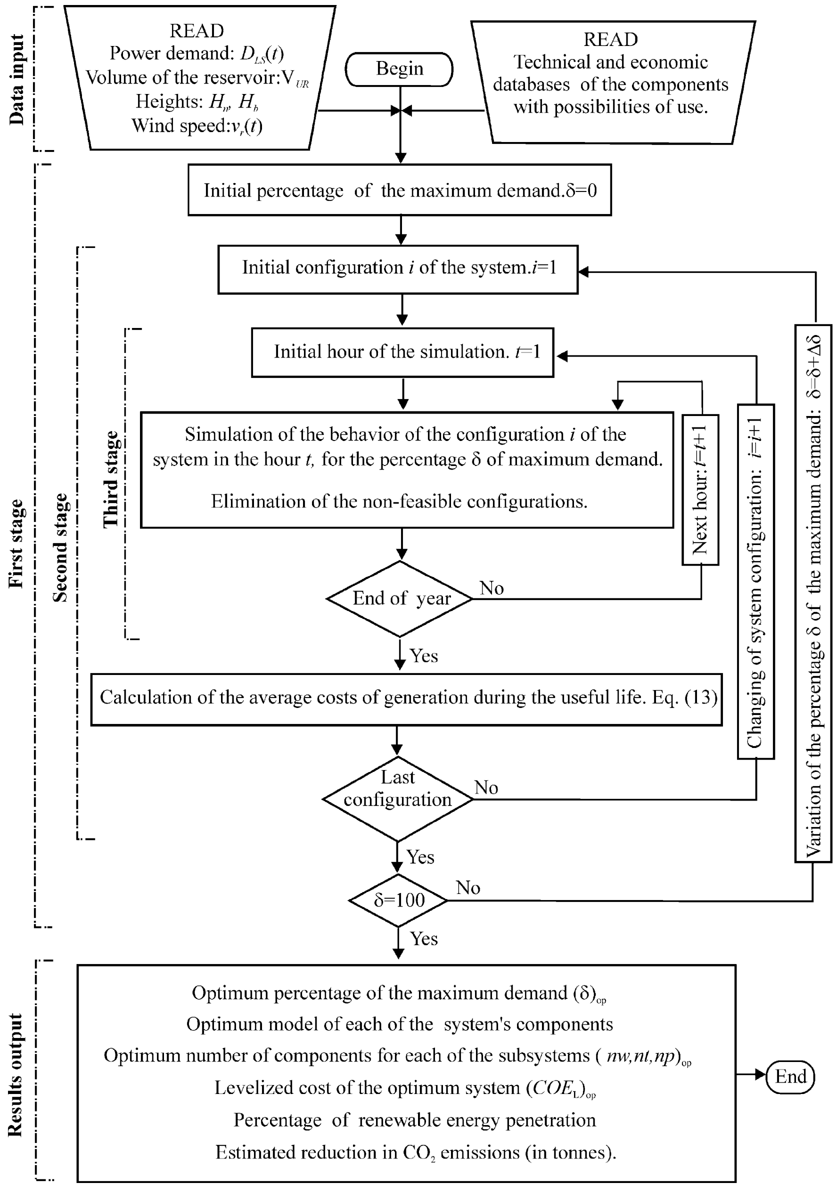

Fig. 4. Algorithm for the selection of the optimum economic renewable system.

act in such a way that Eq. (4)–(6) are met.

$$D_{PS}(t) = n_{pc}(t)Q_p(t)H_b\rho g/\eta_{PS} = P_{WF}(t) \tag{4}$$

$$[D_{LS}(t)]_{base} = P_{CPS}(t) \tag{5}$$

$$[D_{LS}(t)]_{peak} = P_{HP}(t) \quad (6)$$

Other strategies have been described by Bueno and Carta [38] for the system operating configuration system. These estrategies have been applied in El Hierro island [39] (Only 8533 people live on its 268.7 km^2, making it the least inhabited of the Canary Islands), where the objective of the Island Government Council, Unelco (the local electricity company) and the Canary Technological Institute[14] (Spanish initials: ITC) is to cover as much of the energy demand as possible with renewable energy.

In the case of Eq. (4), with the aim of maximising the exploitation of the power $P_{WF}(t)$ generated by the WF, the CS will take advantage of the modularity of the PS by connecting and disconnecting pump sets $n_{pc}(t)$ to adapt the demand profile to the energy supply of the WF. In other words, the objective is for the variations in the energy demand for pumping to be in sympathy with the wind generation.[15] Thus, a positive-feed-forward control is used, i.e. if output is greater than load, load is increased so that constant voltage and frequency are maintained. If load is higher than output, then load is decreased. According to Twidell and Weir [14], this response optimises capital investment and recognises that generation is set by the environment. Moreover, the feasibility of this type of operating strategy has been demonstrated [10]. In Eq. (4), $Q_p(t)$ is the flow pumped by each of the n_{pc} pumps connected, H_b is the pumping height (after accounting for losses), η_{PS} is the efficiency of the PS, g is the acceleration of gravity and ρ is water density.

If δ is the percentage ($0 < \delta < 100$) of maximum hourly demand $D_{LS,max}$ that is to be met by hydroelectric sourced electrical energy, then the profile of the peak demand that has to be covered by hydroelectric energy will be given by Eq. (7) and the profile of the base demand by Eq. (8).

$$[D_{LS}(t)]_{peak} = D_{LS}(t) - D_{LS,max}(1 - \delta/100) > 0 \quad (7)$$

$$[D_{LS}(t)]_{base} = D_{LS}(t) - D_{LS,max}(\delta/100) \geq 0 \quad (8)$$

Under the operating regime of the proposed system the CS controls the different subsystems in accordance with the procedure detailed below in order to maintain the energy balance:

- In respect of satisfying non-controllable demand: the CS will control the CPS in such a way that, at any instant t, it assigns its power $P_{CPS}(t)$ to cover the base demand of the LS non-controllable loads (negative-feed-back control). In periods of peak demand the CS connects the HP, in parallel to the CPS, in order to meet all the non-controllable demand $D_{LS}(t)$ (negative-feed-back control). The power $P_{HP}(t)$ supplied by the HP to cover the peak demand is given by Eq. (9).

$$[D_{LS}(t)]_{peak} = P_{HP}(t) = n_{tc}(t)Q_t(t)g\rho H_n\eta_{HP} \quad (9)$$

[14] Company belonging to the Board of Industry of the Autonomous Canarian Government.
[15] Twidell calls these types of load 'sympathetic loads'.

where $Q_t(t)$ is the volume used by each of the $n_{tc}(t)$ turbines connected at the instant t, H_n is the existing net height, η_{HP} is the efficiency of the HP, which is equal to the sum of the efficiencies of the various elements that participate in the energy production process.

- In respect of the maximum exploitation of the wind sourced energy: the CS will check the WF, at each instant t, and decide, in function of the available power $P_{WF}(t)$, the number of pump sets that have to be connected or disconnected (positive-feed-back control) in order to maintain the electrical balance, Eq. (4). However, a 100% exploitation of the energy that the WF can produce depends on various factors: (a) due to the fact that the pump sets are discrete loads[16] the energy in excess of the energy which can be consumed by a whole number of pumps must be discarded[17] by acting on the regulation system of the WTs [10,40,41],[18] if the restriction indicated in Eq. (4) is to be met; (b) if the upper reservoir UR is full at the instant t it is not possible to connect the pump sets, even if there is sufficient power $P_{WF}(t)$, and so the excess wind energy must remain unexploited.

The electrical energy supplied by a WT at each instant t depends fundamentally on the wind speed at the height h_e of its rotor axle and on the power-speed curve $P_{WT}[v_e(t)]$ [38, 40,42,43]. In the model used here, using a logarithmic law, Eq. (10) [44], the wind speed $v_e(t)$ at height h_e is estimated from the wind speed at the instant t, $v_r(t)$, measured at the reference height $h_r (h_r < h_e)$.

$$v_e(t) = v_r(t)[\ln(h_e/z_0)/\ln(h_r/z_0)] \tag{10}$$

In Eq. (10) it is assumed that the land is flat, homogeneous and with a surface rugosity z_0 [44].

Replacing $v_e(t)$ in the curve $P_{WT}[v_e(t)]$ of the turbine the power $P_{WT}(t)$ generated by that WT at the instant t is estimated. To estimate the power produced by the WF it is assumed that all the WT generate the same power, but the WF power output is corrected using a reliability factor ξ of the WT and a wake factor φ [42]. So, the hourly power $P_{WF}(t)$ generated by the WF will be given by Eq. (11).

$$P_{WF}(t) = (\mathrm{nw})P_{WT}(t)\xi\varphi \tag{11}$$

The volume of water $V(t)$ stored in the reservoir at a time t is given in function of the existing volume $V(t-\Delta t)$, the pumped volume $V_p(t)$ and the volume used by the HT $V_t(t)$:

$$V(t) = V(t-\Delta t) + V_p(t) - V_t(t) \quad \text{with} \quad V(t) \geq V_{min} \tag{12}$$

where V_{min} is the technical minimum volume.

[16] If we start from the hypothesis that these operate in nominal conditions.
[17] The percentage of wind energy rejected for this reason depends on the nominal capacity of each pump set.
[18] Until recently most technologies used to discard this energy were based on the use of dump loads. At the present time, wind turbine technology enables this energy to be discarded precisely by acting on its regulation systems.

3.3. Algorithm for the selection of the optimum economic renewable system

Fig. 4 shows an outline of the base algorithm used to select the renewable system (WF–PS–HP) which maximises the exploitation of a predetermined volume V of the water storage subsystem WS, with the restriction that the unit energy supplied be achieved at minimum cost. This algorithm is based on the hypothesis that all the renewable sourced electrical energy must be accepted by the company which runs the conventional system, even though it may not be profitable for them to do so. This is, in fact, the case in the Spanish State [45].

The algorithm, which commences with a reading of certain basic data, such as the hourly power demand $D_{LS}(t)$ over a year long period, the characteristics of the reservoirs (volume and height), the technical and economic databases of the various commercial equipment used in the study, and the mean hourly wind speeds $v_r(t)$ at the site of the wind farm installation, has various nested iterative stages.

At each iteration of the first iterative loop (Fig. 4), the percentage δ is modified of the maximum hourly demand $D_{LS,max}$ that is to be met with hydroelectric sourced electrical energy, thus modifying, at each iteration, the peak demand profile, Eq. (7).

The purpose of the second iterative stage is to analyse, for each δ, all the systems obtained on combining the different configurations of the subsystems involved (WF, HP, PS) which can be formed when using different models of commercial components and when the installed rated output of the subsystems WF and PS[19] is varied. Thus, at each iteration of the second iterative loop a different configuration of the system is analysed.

In the third stage the annual hourly performance is simulated of each of the combinations of subsystems, which are generated in the second iterative process. In this stage the combinations of components which do not satisfy the peak demand profile or which do not use all the volume V of the reservoir are discarded.

In series with stage 3 a life-cycle costing model (LCCM) is executed [46,47] in order to analyse each of the subsystem combinations which have satisfied the restrictions imposed in the third stage. The model calculates, Eq. (13), the levelized cost of energy COE_L (euros/kW h) [42,48–50] taking into consideration the initial investment costs of the system's commercial components (market unit sale price), the civil works (cost in terms of the size of the civil works), the electrical and hydraulic infrastructure and the engineering and project management (costs proportional to the investment costs of the components) CI_0, as well as the annual operating and maintenance costs $C_{O\&M}$ and the annual external costs, C_{EXT} [51,52].[20]

[19] Though different models of components that make up the HP can be tested, the rated output of this subsystem cannot be modified as we start from the hypothesis that this installed power must cover the maximum peak demand $\delta D_{LS,max}$.

[20] The external costs are made up of the economical estimation of burdens assumed by people and the environment because of energy chains that include the life-cycle of both primary energy sources and power generation plants.

Table 2
Possible transfers between reservoirs

Upper reservoir	Lower reservoir	Height (m)	Distance (km)	Usable volume (h m^3)
Cueva Las Niñas (1)	Soria (7)	270.00	1.8	5.00
Chira (2)	Soria (7)	281.00	2.5	5.00
Las Hoyas (3)	Lugarejos (4)	68.00	1.3	1.10
Lugarejos (4)	Los Pérez (8)	43.00	0.54	1.50
Parralillo (5)	Caidero de la Niña (9)	127.00	3.05	2.00
Siberio (6)	Caidero de la Niña (9)	34.00	3.48	2.00

$$\mathrm{COE_L} = \{(\mathrm{CI}_0 - S_0)r/[1-(1+r)^{-L}] + C_{\mathrm{O\&M}} + C_{\mathrm{EXT}}\}/\int_0^{8760} [D_{\mathrm{LS}}(t)]_{\mathrm{peak}}\,\mathrm{d}t \tag{13}$$

where r is the annual discount rate (opportunity cost), L is the number of years over which the investment in the system is to be recovered and S_0 is an initial subsidy.

In the final stage, the percentage of maximum demand that can be covered at minimum cost is selected together with the optimum economic renewable system configuration (model and number of components of each subsystem), and the results are presented.

4. Data of the system under study

Among the various reservoirs that can, in principle, be used to transfer water with the aim of exploiting its potential energy through the installation of hydropower systems (Table 2 and Fig. 1), the reservoirs named Soria and Chira have been chosen (Fig. 2). These have the highest capacities on the island as well as the greatest difference in height (281 m). It should be mentioned that to involve in this study the other reservoirs, taking into consideration the different installable powers and the probable different generating costs, would require the execution of a global load optimum dispatching model [16,53,54], which is beyond the scope of the present paper.

The monthly evolution, between 1990 and 1998, of the total volume of water in the two selected reservoirs is shown in Fig. 5.

To select the optimum economic configuration of the system the following have been used: commercial wind turbines with rated outputs of between 600 and 1500 kW (Fig. 6); pumps with rated outputs of between 24 and 800 kW (Table 3); and 6 Pelton turbines with rated outputs of between 1500 and 15,000 kW (Table 4).

In the area chosen for the installation of the wind farm[21] (Fig. 1) the ITC took measurements, at 10 m above ground level, of the wind speed and direction between the years 1998 and 2000. With the aim of classifying these years in terms of wind speed and intensity, comparisons[22] have been made, using the model proposed by Corotis

[21] The south-east coastal area of the island is flat, with no obstacles to the predominating NE winds. The land rugosity can be estimated at 0.03 m [42], for the purpose of extrapolating wind speed with height.

[22] The existing correlation coefficient between the recorded wind speeds at the airport and at the site proposed for the installation of the wind farm is very high.

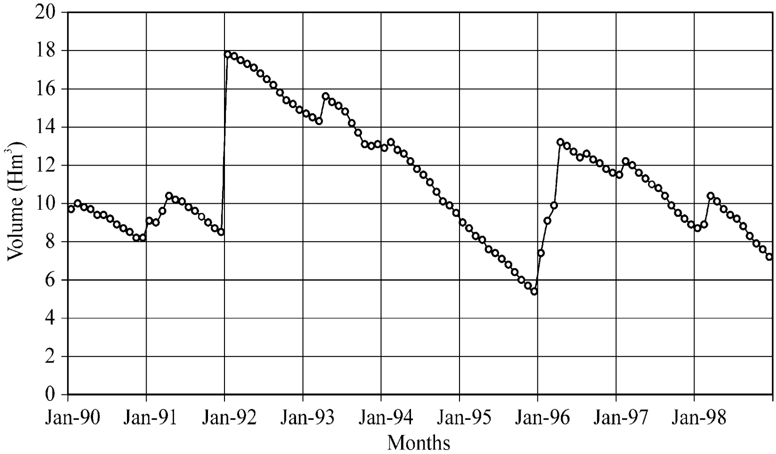

Fig. 5. Evolution of the total volume of water in the reservoirs of Soria and Chira between 1990 and 1998.

[8,55,56,57], with the wind speed records recorded between 1980 and 2000 at Gando airport (Fig. 1). From the analysis it was seen that the year 2000 was representative of a year of low wind speeds. With the idea of making a conservative based study, the hourly wind speeds recorded over the year 2000 have thus been used. The work of Justus [58] and Ramsdell et al. [59] indicates that the annual average wind speed as found from 12 months of data recording will be within 10% of the true log term average wind speed with a 90% confidence level. According to Cherry [60], the wind is generally more consistent at sites with higher average wind speeds.

The annual mean wind speed (Fig. 7) in the year 2000 was 7.93 m s^{-1}, blowing with greatest intensity in the months of July (11.89 m s^{-1}) and August (10.89 m s^{-1}) due to

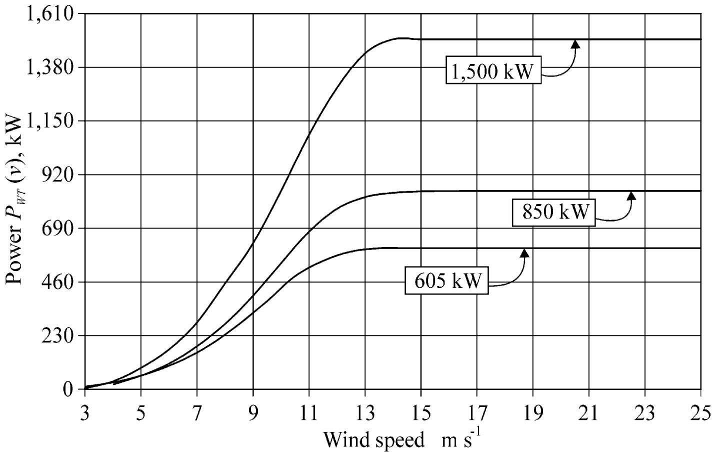

Fig. 6. Power curves of some commercial wind turbines.

Table 3
Nominal characteristics of the tested pumps

Power (kW)	24	44	62	83	100	120	155	200	300	372	800
Flow ($m^3\,h^{-1}$)	18	36	54	72	90	108	144	185	288	360	870
Efficiency (%)	63	67	71	71	73	74	76	76	79	79	80

Table 4
Nominal characteristics of the hydraulic turbines tested

Power (kW)	1500	3000	6000	10,000	12,000	15,000
Flow ($m^3\,h^{-1}$)	2496	5004	9972	16,632	19,963	24,968
Efficiency (%)	90	90	90	90	90	90

the higher predominance of the trade winds, a typical feature in the Canarian Archipelago. The average daily wind speed in the area chosen for the wind farm is shown in Fig. 8. This figure makes a division between those months (June, July, August, September and October) whose mean wind speeds are higher and those months which are lower (January, February, March, April, May, November and December) than the annual mean wind speed of 7.93 m s^{-1}. The first group of months have been called type H (higher than the annual average) and the second group type L (lower than the annual average).

The evolution of the island's electricity demand for the year 2002 is shown in Fig. 9, together with the peak and minimum hourly power demand of each month. The mean daily evolution of power demand is shown in Fig. 10. It can be seen that the hourly mean power demand has demand peaks during two periods, between approximately 10:00 and 14:00 and between 18:00 and 23:00.

5. Numerical results for the model under study

The results of the studies undertaken show that the percentages δ of maximum demand that can be covered by the system in an optimum economic manner depend on the seasonal

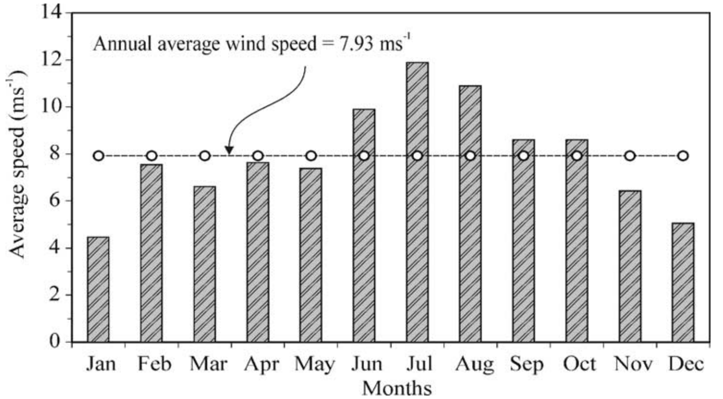

Fig. 7. Evolution of the monthly wind speeds during 2000.

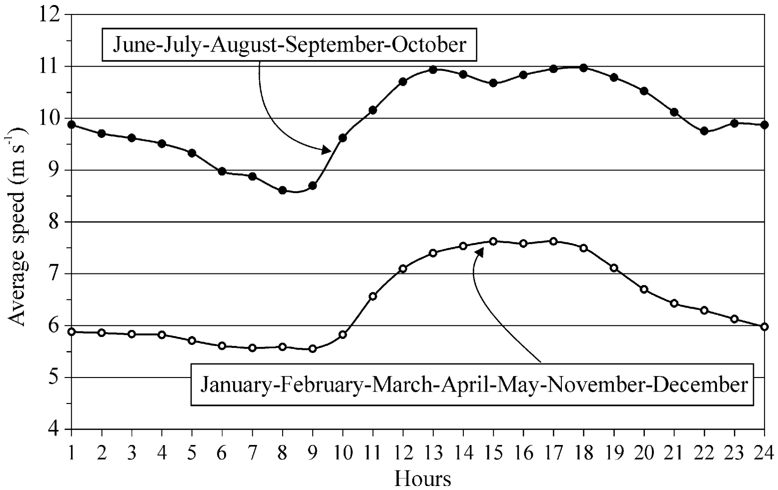

Fig. 8. Average daily wind speed evolution.

period of the year. Thus, in months covered by H the optimum percentage was 12%, while for months covered by L the corresponding figure was 8%. These percentages give rise to daily mean peak demand profiles that can be covered, for months L and months H, as shown in Fig. 11.

The configuration of the renewable system which provides the minimum cost of the unit energy supplied (0.084 euros/kW h) consists of 24 WT with a rated output of 850 kW, 89 pumps with a rated output of 200 kW and six hydraulic turbines with

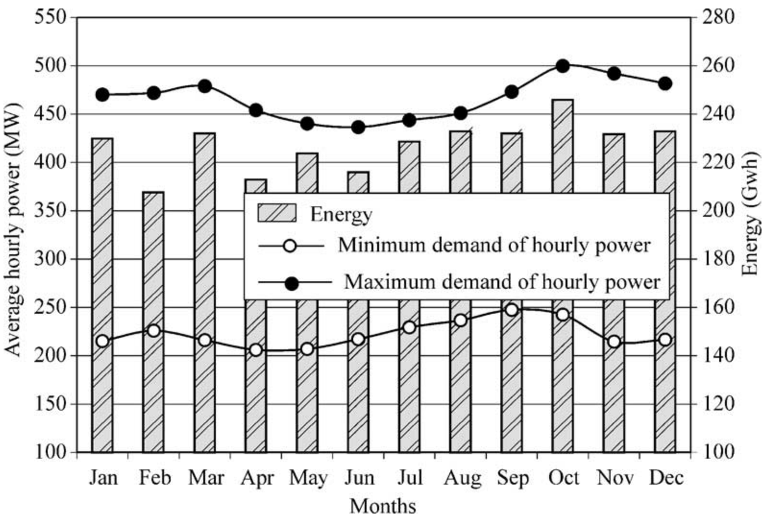

Fig. 9. Evolution of energy demand and maximum and minimum hourly output.

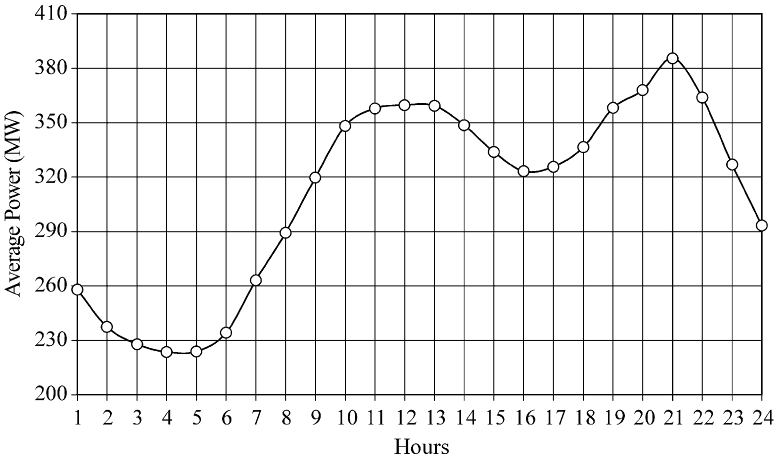

Fig. 10. Average daily power demand profile for the island of Gran Canaria.

a rated output of 10 MW. This configuration was obtained with a projected useful life of 20 years, an annual discount rate of 0.07, investment costs of 32.1 million euros, annual maintenance costs for all the subsystems of 1.2 million euros, and estimated average external costs for the wind and hydraulic energy cycles of 0.185 million euros. To estimate the external costs the average measured costs in Europe have been employed [61–63].

The cost per unit energy supplied of the present conventional system during peak demand periods is 0.084–0.096 euros/kW h, similar to the cost of the proposed system. If we add to this conventional specific cost externality costs due to the fuel cycle (0.08 euros/kW h)[23] then the difference in cost between the two systems shows a marked increase. In this respect, it should be remembered that an official statement from the European Communities Commission on the execution of the first phase of the European Climate Change Programme proposed the use of the criteria of 20 euros per equivalent tonne of CO_2 as an appropriate cost/efficiency ratio [64]. These results corroborate the studies realized by Roth and Ambs [52]. These authors indicate that incorporating externalities has a large impact on the COE_L and the relative attractiveness of electricity generation options. In addition, in conventional systems the fuel cost entails a high percentage of the specific cost of electricity generation, and this cost has an upward trend [65].

Fig. 12 gives the results obtained from the simulation of the seasonal performance of the proposed system using the recorded hourly wind speeds over the year 2000. This figure shows the estimated obtainable wind sourced electrical energy, the energy consumed in water pumping and the electrical energy fed into the grid by the hydroelectric plant. It can be seen that a higher percentage of renewable sourced energy is fed into the grid during the months H, as in these months a higher water pump flow

[23] To estimate these costs the average measured costs in Europe have been used.

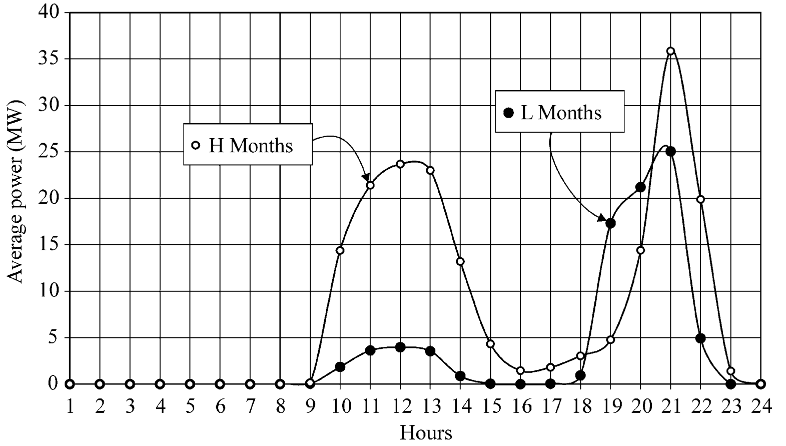

Fig. 11. Average daily peak demand profiles that can be covered in months L and in months H.

can be achieved. This, in turn, is a consequence of the higher intensity of the wind speed (Fig. 7) and the non saturation of the volume of the upper reservoir due to the greater energy demand.

It should be pointed out that in the model used the system is designed for optimum annual economic performance. However, due to the characteristics of the wind and the demand, the rated output of the WF is not optimally exploited during all the months of the year from a technical point of view. Figs. 12 and 13 show how, during the months of March, April and May, there is a high percentage of electrical energy that could be extracted from the wind but is not exploited. This is primarily due to the fact that

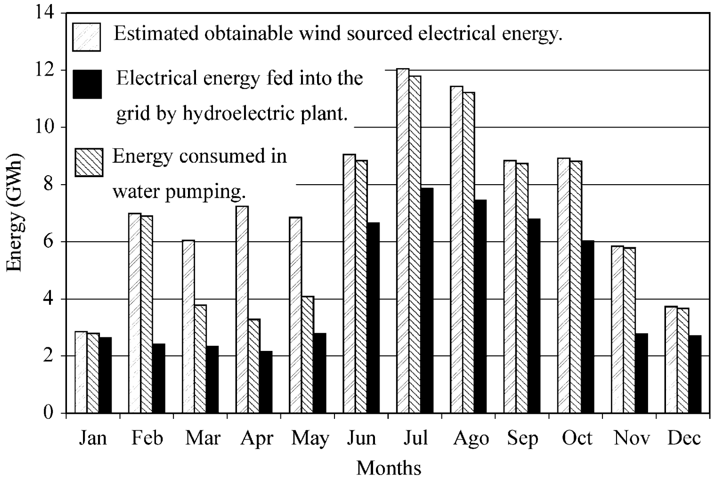

Fig. 12. Simulation of the seasonal performance of the proposed system.

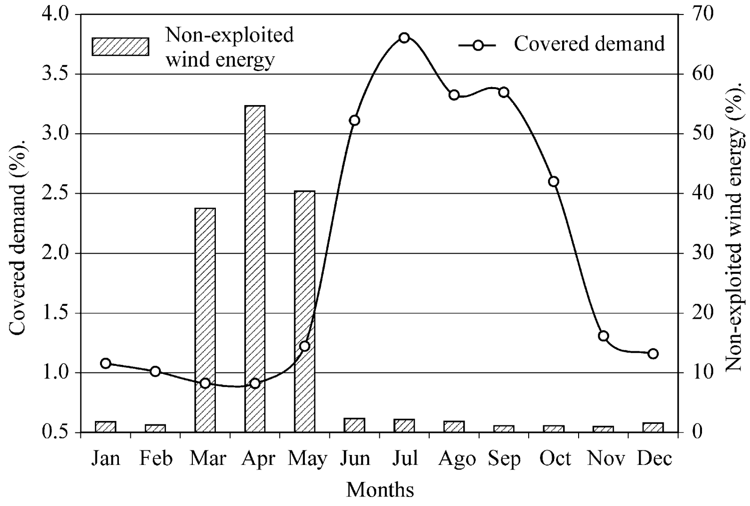

Fig. 13. Percentages of covered energy demand and unexploited wind energy.

the upper reservoir is full most of the time (Fig. 13) and, therefore, the CS does not order the connection of pumps that would consume the energy that can be supplied by the WF. The regulation and control mechanisms of the WF have to act to get rid of the excess kinetic energy from the wind [10]. As can be seen in Fig. 13, during the rest of the year the non-exploited producible energy of the WF is minimal. This non-exploitation is due to the loads of the pump sets being discrete and therefore unable to match perfectly the energy supply curve of the WF [8]. For the simulated year, some

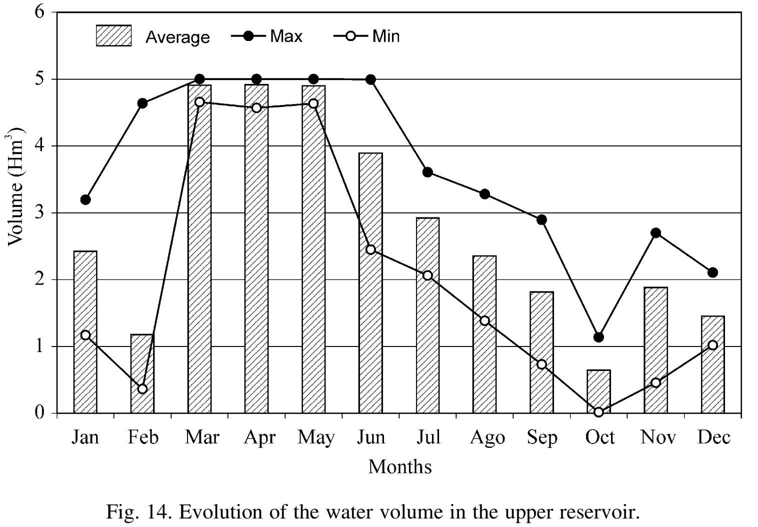

Fig. 14. Evolution of the water volume in the upper reservoir.

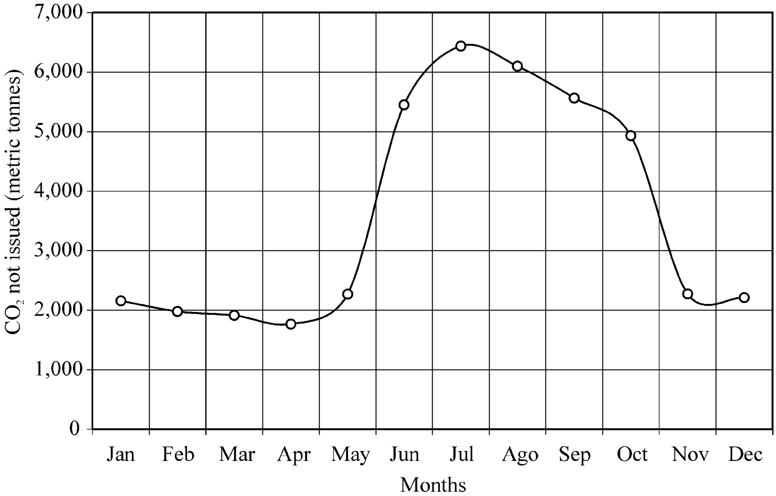

Fig. 15. Seasonal evolution of the amount of CO_2 not emitted into the atmosphere.

11.28% of the energy that can be generated by the WF is not exploited for these two reasons. This means that the capacity factor [40] of the WF decreases from 50.25 to 44.58%. However, this remains a relatively high value. It also ought to be mentioned that, as a result of the peculiarities of the proposed system, the so-called characteristic operating time of the hydroelectric plant, in other words the ratio between annual production and installed power, is relatively small (876 h), if compared with hydroelectric plants in operation in Spain [66], which have a characteristic operating time of more than 2000 h. Decidedly higher is the characteristic operating time of the pumping station, which reaches a figure of 4065 h.

It can be seen in Fig. 14 that during the months of March, April and May the fluctuation in the volume of water in the upper reservoir is relatively low. The optimisation model used allows for a large volume of water to be available in the upper reservoir in the months prior to the seasonal period of highest demand (months H), as water pumping during the months H is not enough to cover, from an optimum economic point of view, demand (Fig. 14).

Likewise, in Fig. 13 it can be seen that the percentage of monthly electricity demand on the island that is covered by this wind sourced energy during each of the months H is higher than 2.5%, while in the remaining months this wind penetration is approximately 1%. Thus, with the proposed system an overall increase can be achieved of 1.93% (52.55 GW h/year) in annual penetration of renewable sourced energy. This would entail a fossil fuel saving of 13,655 metric tonnes/year and, consequently,[24] a total of 43,064 metric tonnes less of CO_2 would be emitted into the atmosphere each

[24] Average relation determined for the following fuel oil (whose sulphur content is less than or equal to 1%. Density: 0.99 kg/l (15 °C). Inferior calorific power: 9700 kcal/kg. Superior calorific power: 10,200 kcal/kg. Viscosity kinematic is less than or equal to $380\times10^{-6}\ m^2\,s^{-1}$. (50 °C). Ask: 0.06% m/m).

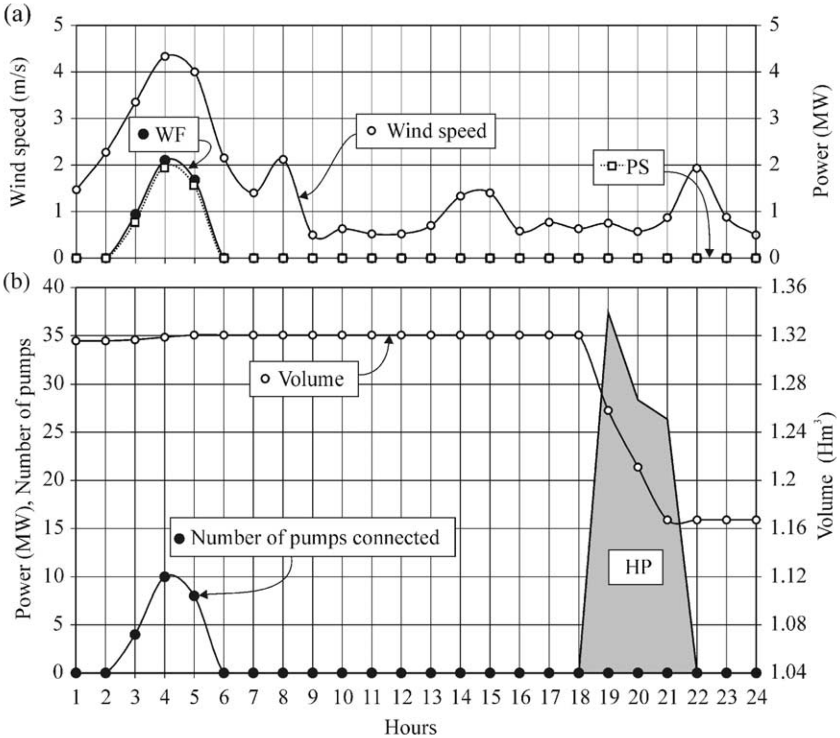

Fig. 16. Simulation of the system operation over 1 day in the month of January.

year. As can be seen from Fig. 15, in the month of August alone a reduction in CO_2 emissions of 6000 metric tonnes would be achieved. Actions whose figures are of such clear help in combating climate change are actions that are sorely and urgently needed [64,67].

Fig. 16 shows an hourly simulation of the operation of the proposed renewable system over the course of 1 day in the month of January. Fig. 17 shows the same simulation, but for 1 day in the month of July. It can be seen from Figs. 16(a) and 17(a) that the system operates with 'positive feed-forward' [10,14]. In other words, the variation in energy demand for pumping is in sympathy with the wind generation, with the aim of optimising the exploitation of the wind energy. Figs. 16(b) and 17(b) show how the number of pumps that are connected varies over the course of the day to adapt to the wind energy supply. Likewise, it can be seen that the variations in wind speed (Figs. 16(a) and 17(a)) have no effect on meeting the demand with hydraulic sourced electrical energy thanks to the intervention of the storage deposits.

Finally, it can be seen that during the type of month L (Fig. 16(b)) less peak demands are covered and for a shorter period of time than in months H (Fig. 17(b)).

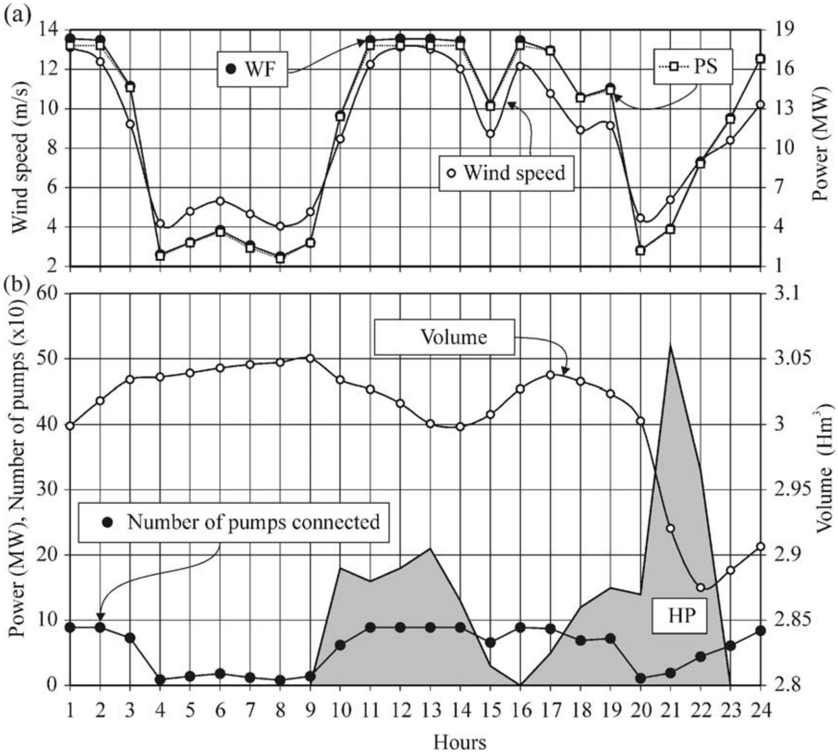

Fig. 17. Simulation of the system operation over 1 day in the month of July.

6. Conclusions

A proposal is presented in this paper to mitigate the problem of the restriction of wind sourced energy penetration in the island grid of Gran Canaria (Canarian Archipelago) via the installation of a wind powered pumped hydro storage system. The proposed system, based on the use of existing water reservoirs and on energy consumed by the pumping system being in sympathy with the wind generation, allows progress to be made in the attainment of the objectives set out by the European Union in energy related matters since: (a) the results obtained from the application of an optimum sized economic model of a wind powered pumped hydro storage system show that an increase in renewable sourced energy penetration of 1.93% (52.55 GW h/year) is possible at a competitive cost for the unit energy supplied, if costs arising from damage to health and the environment associated with the production and use of energy are taken into consideration. That is to say, the clean and efficient proposed generation system is the most attractive when all options are examined using externalities. (b) The proposed system would have no effect on the reliability of the electrical system nor on consumer satisfaction, and would entail a fossil fuel saving of 13,655 metric tonnes/year and a reduction in CO_2 emissions of 43,064 metric tonnes/year.

The system described in this paper successfully combines a maximum exploitation of this renewable energy source with the maintenance of a quality electricity service. Therefore, for regions that have topographically suitable sites and which suffer energy problems similar to those of the Canary Islands it is proposed that an analysis be made of the technical and economic feasibility of the installation of such power systems. Within the general guiding framework of a policy promoting clean and renewable energy, these systems represent an enormous and as yet barely explored potential.

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